

Advancing Timber for the Future Built Environment

# MODELLING OF CROSS-LAMINATED TIMBER PANELS SUBJECTED TO CONTACT CHARGE DETONATIONS AND NEAR-FIELD BLAST LOADS

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**ABSTRACT:** Despite recent progress in terms of developing protective design provisions and standards for mass-timber structures against far-field blast loads, little to no work has been conducted on how these relatively novel systems behave under close-in live explosives. This paper presents the results of a numerical study investigating the behaviour of cross-laminated timber (CLT) panels subjected to contact charge detonations and near-field blast explosions. The finite element software LS-DYNA was utilized, with material inputs derived from the built-in model and recent experimental test programs. Experimental contact and near-field blast testing was conducted to be used for the validation of the model, where the modelling results showed good agreement. This numerical modelling tool will allow for the response of mass-timber elements subjected to contact charge detonations and near-field explosions to be predicted without the need for costly experimental blast testing.

KEYWORDS: Blast loads, timber, cross-laminated timber, LS-DYNA, finite element analysis

# **1 – INTRODUCTION**

Improvements in wood technology and design provisions, along with the need for sustainable infrastructure, have led to a shift in the public's perspective regarding the use of mass-timber in construction. The use of engineered wood products, such as cross-laminated timber (CLT), in mid-rise and highrise construction is increasing. However, due to its brittle nature in tension and flexure, wood structures may be prone to collapse if key elements are damaged or brought to failure, possibly leading to progressive collapse. This is of particular importance for buildings and infrastructure with force protection requirements, such as those against forced entry and blast loads. Near-field and contact explosion events are generally characterized by high-temperature fireballs, accompanied by highmagnitude, non-uniform overpressures. Such loading is often difficult to study experimentally due to the catastrophic nature of the loading event and short load duration. Paired with live-arena blast testing being logistically difficult and costly, researchers often turn to numerical models to understand and predict how structural elements will perform under these extreme loads. The majority of the published research on the effects of contact charge detonations and near-field blast loads have focused on reinforced concrete and steel structures [e.g., 1-2]. While far-field blast loads, which are assumed to act as a uniformly distributed pressure (i.e. planar blast loads) on timber elements have been studied extensively via experimental testing [e.g., 3-10] and numerical methods [e.g., 11-12], little-to-no published work currently exists on how mass-timber behaves under contact charge detonations and near-field blast loads.

The current study introduces a finite-element (FE) model for CLT panels developed within the explicit LS-DYNA environment [13], focusing on the application of the built-in wood material model to effectively represent the complexities of CLT. Utilizing the software's capability and built-in material model to accurately generate and simulate close-in blast explosions and their effects, the model can investigate how CLT panels perform under various numerically simulated contact and near-field explosions. This study has the potential to significantly influence the development of blast standards such as the Canadian blast standard, CSA S850 [14], by providing valuable insights and data.

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# **2 – LITERATURE REVIEW**

There is a scarcity of research on timber components subjected to near-field and contact blast loading scenarios. Qiu et al. [15] investigated the performance of two types of bamboo panels-parallel bamboo strand lumber (PBSL) and cross-laminated bamboo (CLB)through near-field and contact explosion experiments. In near-field explosions, the primary failure mechanisms of PBSL included matrix cracking and fiber breakage, while CLB predominantly experienced fiber fracture and spalling. In contact charge detonations, both PBSL and CLB panels underwent breaching failure, resulting in a through-hole at the center of the panels. The CLB panel showed a significantly smaller breach compared to the PBSL. Notably, at the same scaled distance under nearfield scenarios, PBSL exhibited fiber fractures, whereas CLB remained in the elastic state, highlighting its superior blast resistance. Additionally, the CLB panel experienced a significantly smaller breach under contact charge detonations, demonstrating its enhanced ability to withstand blast effects. Research on laminated bamboo plates (LBPs) has demonstrated their excellent blast resistance under near-field and contact explosive loading conditions [16]. Three sorts of LBPs were studied: flatpressed unidirectional plates (PR), flat-pressed perpendicular plates (PC), and side-pressed unidirectional plates (PT). Experimental results revealed distinct damage patterns, including through-thickness cracks, fiber rupture, spalling, and breaching, with the orthogonal structure (PC) effectively mitigating throughthickness cracks. LBPs demonstrated good elasticity, structural stability, and residual load-bearing capacity under explosive loads, with orthogonal and side-pressed plates improving their ability to carry loads [16].

The single-degree-of-freedom (SDOF) modelling approach has been foundational in conducting dynamic analysis of blast effects on structures. The SDOF approach simplifies a complex structural member into a system with a single mass and stiffness [17], allowing for a computationally effective methodology to determine dynamic response. Several studies have applied SDOF models to timber elements under blast loads and impacts [e.g., 4-10], effectively capturing maximum deformation and overall behaviours. Despite its computational efficiency, SDOF modelling does not inherently capture detailed local stress distributions, progressive failure propagation, or the extent of damage within a structural element which are critical in accurately predicting damage under close-in blast conditions. Finite element modelling (FEM) offers a more comprehensive alternative by enabling detailed simulations that consider material heterogeneity, geometric nonlinearities, and localized failure mechanisms. The application of FE models has proven advantageous in capturing stresses and strains within timber members and damage initiation under far-field blast loads. Oliveira et al. [11] investigated the behaviour of glued-laminated timber (glulam) beams and CLT panels under far-field simulated blast loads using finite element analysis (FEA), offering improved predictive capabilities compared to simpler analytical models such as SDOF.

A notable gap exists in the literature regarding the FE analysis of timber elements subjected to near-field or contact explosions. This research void may stem from the heightened complexity of simulating close-range blast effects, where extreme load intensities and high strain rates complicate model formulation and validation. Additionally, the scarcity of experimental data for nearfield and contact scenarios hinders the development of robust FE models for these conditions. Addressing these challenges is crucial for advancing the comprehension of timber behaviour under severe blast loads and designing safer timber structures. The present study proposes an advanced FE model tailored to simulate the performance of CLT panels under near-field blast loads and contact charge detonations.

### **3 – FINITE ELEMENT MODEL**

### **3.1 MODEL DESCRIPTION**

The explicit solver for FEA in LS-DYNA [13] was utilized to analyze the time-dependent behaviour of CLT panels subjected to contact charge detonations and near-field blast loads. The LOAD\_BLAST\_ENHANCED (LBE) keyword in LS-DYNA has been adopted to simulate blast pressure. This approach involves obtaining the blast pressure from the empirical equations developed by Kingery and Bulmash [18] and then directly applying it to the structure's shock-front surface. Previous studies [e.g., 1, 19] have demonstrated that the LBE method in LS-DYNA can generate blast loading with sufficient accuracy for assessing the behaviour of structural members subjected to near-field blast loads.

The LS-DYNA LBE method is based on empirical fitted curves that are valid within a specific range of scaled distances (e.g., for spherical free-air bursts:  $0.147 < Z < 40 \text{ m/}\sqrt[3]{\text{kg}}$  [20]. At a null or near-null standoff distance ( $Z \approx 0$ ), the method falls outside this validated range,

which is why contact explosions are generally modeled using the Arbitrary Lagrangian-Eulerian (ALE) method in LS-DYNA [e.g., 21-22]. However, utilizing the ALE approach requires significantly higher computational cost to mode, due to the need to model both the charge and the air domain with a fine mesh. For this preliminary study on CLT panels under contact explosions, a minimal non-zero standoff distance of 2 cm was introduced. This slight offset is a practical compromise: it avoids the convergence issues at Z = 0 while closely approximating the contact condition. Although this approach is not ideal, it allows for efficient parametric studies and provides useful insights that can guide subsequent, more detailed analyses using the ALE method.

A finite element model was developed to predict the response of CLT panels under live contact and near-field explosions. In all analyses, three-dimensional eight-node solid first order elements were employed. The mechanical behaviour of CLT panels was modelled as a transversely isotropic material using the wood material model currently available in LS-DYNA software, Material Type 143, whereby damage initiation and propagation are defined using a reduced form of the Modified Hashin failure criteria [23]. The model can predict both parallel and perpendicular to the grain tensile and compression failures, as well as parallel and perpendicular shear failures, using six strength parameters derived from uniaxial and pure-shear tests. The model utilizes the Hashin criteria in the parallel- and perpendicular-to-grain directions, as demonstrated in Equations (1) and (2), respectively [23]. Failure occurs when  $f_{\parallel}$  and  $f_{\perp}$  are equal to or greater than zero.

Element erosion was enabled in the model to account for parallel damage, where cracking occurs across the grain, effectively breaking the wood fibres. When an element experiences severe parallel damage and fails in the parallel mode, it is automatically removed, ensuring a realistic representation of material failure. This approach helps prevent computational difficulties due to an element's extremely low stiffness and strength.

$$f_{\parallel} = \frac{\sigma_{L}^{2}}{x_{\parallel}^{2}} + \frac{(\sigma_{LT}^{2} + \sigma_{LR}^{2})}{s_{\parallel}^{2}} - 1 \qquad \qquad X_{\parallel} = \begin{cases} X_{T} \text{ for } \sigma_{L} > 0 \\ X_{C} \text{ for } \sigma_{L} < 0 \end{cases}$$
(1)

$$f_{\perp} = \frac{(\sigma_R + \sigma_T)^2}{Y_{\perp}^2} + \frac{(\sigma_{RT}^2 \cdot \sigma_R \sigma_T)}{S_{\perp}^2} - 1 \qquad Y_{\perp} = \begin{cases} Y_T \text{ for } \sigma_R + \sigma_T > 0\\ Y_C \text{ for } \sigma_R + \sigma_T < 0 \end{cases}$$
(2)

 $X_T$  (the tensile strength parallel to the grain) represents the maximum tensile stress wood can withstand along its grain direction before failure. In contrast,  $X_C$  (the compressive strength parallel to the grain) defines its capacity to resist compressive forces along the same Similarly, Y<sub>T</sub> (the tensile strength direction. perpendicular to the grain) measures the wood's resistance to tensile forces applied across the grain, whereas Y<sub>C</sub> (the compressive strength perpendicular to the grain) quantifies its ability to endure compressive loads in that direction. Additionally, wood exhibits distinct shear properties, with  $S_{\parallel}$  (the shear strength parallel to the grain) and  $S_{\perp}$  (the shear strength perpendicular to the grain)  $\sigma_L$  is the longitudinal (parallel) stress, while  $\sigma_R$  is the radial (perpendicular) stress, and  $\sigma_T$  is the tangential (perpendicular) stress.  $\sigma_{LR}$ is the longitudinal-radial shear (parallel) stress,  $\sigma_{LT}$  is the longitudinal-tangential shear (parallel) stress, and  $\sigma_{RT}$  is the radial-tangential shear (perpendicular) stress.

#### **3.2 - MODELLING INPUTS & SPECIMENS**

The test configuration and specimens from an ongoing experimental study investigating the behaviour of CLT panels subjected to contact charge detonations and nearfield explosions were utilized to evaluate the finite element model and modelling approach. The experimental testing was conducted at the Canadian Explosives Research Laboratory (CERL). A blast tank was used to conduct the series of explosives tests, allowing for charges of up to 2 kg of C4 to be used. As shown in. Fig. 1, the test specimens were placed on a steel reaction frame with rollers at the ends to simulate simply supported boundary conditions, allowing for rotation. In addition, rollers placed on the top (compression) side of the specimens loosely fastened down to the reaction frame were used to ensure that the specimens could rebound without being projected off of the test frame. Instrumentation included four load cells to capture reaction forces at the ends of the panels, three strain gauges at mid-span, two linear potentiometers, and two laser sensors placed on the underside of the panel. The laser sensors captured the mid-span displacement-time history at the centre of the panel, while the LVDTs were used to measure the mid-span displacements across the width of the panel to capture non-uniform displacement patterns across the cross-section.

E1 grade spruce-pine-fir (SPF) CLT panels were used as part of the validation, with thicknesses of 105, 175 mm, and 245 mm corresponding to a 3-ply, 5-ply, and 7-ply panels, respectively. The width and the length of all panels were 1,050 mm and 2,100 mm, respectively. Testing was carried out using composition-4 (C4) high explosives of varying charge weights. In all tests, the explosive was positioned at the center of the mid-span point of the CLT specimens. A 1.28 TNT equivalency factor was, which is the average between pressure and impulse equivalent weights of TNT [24]. The equivalent TNT weight of the explosive used in the experimental test and its location were specified in the LBE keyword to estimate and establish the experimental blast pressures in the FEA environment.



Figure 1. Experimental test setup

The FEA model was developed to replicate the experimental specimens, boundary conditions, and loading conditions. Inputs for the material model related to wood properties were obtained from manufacturer specifications and published literature. *Table 1* summarizes all inputs used in the FEA model.

It was determined that the recommended value for  $G_{TR}$  in the literature [11] is incompatible with those applied in the MAT-143 built-in material model, which requires that  $E_T$  must be less than four times the value of  $G_{TR}$ . Considering that  $G_{TR}$  and  $E_T$  are interdependent, the  $G_{TR}$ value referenced was adjusted in this study to meet the requirements of the MAT-143 material model [13, 23], however, the assigned value still falls within the expected range for this parameter. The experimentally tested and modelled CLT panels consisted of separate longitudinal and transverse layers. In the FEA environment, it was assumed that there was a perfect bond between the layers of the CLT panel. As illustrated in Fig. 2, additional experimental elements, such as the pinned boundary conditions, were also incorporated. The boundary supports were represented by four cylindrical rigid bodies that functioned as pinned supports to simulate the boundary conditions utilized in the full-scale experimental tests. A mesh size of 17.5 mm was chosen for the CLT model as it offered a reasonable balance between result accuracy and computational efficiency. Furthermore, this mesh size was selected to ensure that each ply's depth was discretized using two elements. The predicted results, including displacements and failure modes, were then compared with the experimental test data to evaluate the accuracy of the FE model's predictions.

Table	1:	Material	properties	modelling	inputs
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Property	CLT CLT		Ref.				
	(Long.)	(Trans.)					
E <sub>L</sub> (Parallel-to-Grain Elastic	11700	9000	[11]				
Modulus)	MPa	MPa					
E <sub>T</sub> (Perpendicular-to-Grain Elastic Modulus)	390 MPa	300 MPa	[11]				
G <sub>LT</sub> (Parallel shear modulus)	731 MPa	563 MPa	[11]				
G <sub>TR</sub> (Perpendicular shear	100 MPa	80 MPa	[13,23]				
modulus)							
$v_{IT}$ (Parallel major Poisson's	0.47	0.47	[11]				
ratio)							
$X_{T}$ (Parallel tensile strength)	27.7 MPa	5.8 MPa	[11]				
X <sub>c</sub> (Parallel compressive	34.7 MPa	16.2 MPa	[11]				
strength)							
Y <sub>T</sub> (Perpendicular tensile	1.4 MPa	1.4 MPa	[11]				
strength)							
Y <sub>C</sub> (Perpendicular	8 MPa	8 MPa	[11]				
compressive strength)							
S <sub>  </sub> (Parallel shear strength)	10.9 MPa	10.9 MPa	[11]				
S <sub>1</sub> (Perpendicular shear	27 MPa	27 MPa	[25]				
strength)							
GF <sub>11</sub> (Parallel fracture	6 N/mm	6 N/mm	[11]				
energy in tension)							
GF <sub>21</sub> (Parallel fracture	84 N/mm	84 N/mm	[23]				
energy in shear)							
GF <sub>11</sub> (Perpendicular fracture	0.4 N/mm	0.4	[23]				
energy in tension) N/mm							
GF <sub>21</sub> (Perpendicular fracture	0.8 N/mm	0.8	[23]				
energy in shear)		N/mm					

### 4 - RESULTS AND DISCUSSION

Validation of the FE models was conducted using experimental results for CLT panels subjected to contact charge detonations and near-field blast loads. The FE modelling results were evaluated based on the displacement-time history and overall observed damage. The displacement-time histories were obtained from midspan nodes on the tension side of the modelled CLT specimens to be compared with experimental test results. The numerical results are compared and discussed alongside the corresponding experimental test data in this section. Overall, the numerical results captured the overall failure mode of specimens, whereby failure initiation can be seen as occurring near mid-span. Failure mechanisms for near-field and contact scenarios were observed to differ substantially throughout testing, as expected, from breaching due to contact charges to tensile failure of the outer plies leading to flexural failure under near-field blast loads.



Figure 2. Modelled test setup for CLT in LS-DYNA

Table 2 summarizes the findings from three experimental tests on 3-ply specimens, and the associated numerical FE analysis, including the predicted and experimental mid-span displacement at failure. On average, the model overpredicted displacement at initial failure by 9.9% (COV = 16.5%), with maximum absolute errors of 28.6%. A representative displacement-time history from both experimental and numerical data is shown in *Fig. 3* for a 3-ply CLT panel subjected to 1 kg of C4 at a 0.5 m standoff distance. Although the FE model captures both the inbound and rebound phases of the response, the comparison with experimental results is limited to the maximum response up until initial failure of the CLT panel, due to the complexity in capturing post-peak failure in wood structural elements [11].

Fig. 4 compares experimentally observed and numerically predicted damage. This experimental test

resulted in flexure failure of the panel, likely initiated on the tension-side laminate at a finger joint failure. The results indicate that FEA modeling can predict the overall failure mode of CLT panels under near-field blast loading, however, further refinements are needed for the model to be able to capture post-peak damage propagation experienced by CLT specimens in FE simulations under near-field blast loading.

Table 2: Summary of Numerical and Experimental Results

	Tes	Displacement at				
			failure			
Test					(mm)	
	Specimen	Charge	Standoff	Exp.	Num.	Err.
		(kg).	(m)			(%)
1	3-ply	1	0.5	36.5	33.7	-7.7
2	3-ply	1	1.0	17.0	18.5	+8.8
3	3-plv	2	0.5	4.9	6.3	+28.6



Figure 3. Representative experimental and predicted displacementtime histories (at the centre of the specimen)



Figure 4. Representative modelling results and corresponding experimental test of near-field blast loading for a 3-ply specimen

The FE model demonstrates the suitability of LS-DYNA and the built-in material model (143) in capturing the dynamic behaviour of CLT panels under near-field explosions. As these blast scenarios entail temporally and spatially non-uniform pressure-time histories, this often leads to a combination of local and global damages and failure modes in the CLT specimens. In such cases, FEA presents itself as an appropriate modelling methodology to accurately predict displacement-time histories, damage levels, and failure modes. While more simplified modelling methods can be used to model far-field blast explosions, such as equivalent SDOF modelling, these may be unsuitable for near-field blast loads, due to the prominence of localized damage and non-uniform loading and complex deflected shapes.

For the sake of comparison for contact charge detonations, experimental and numerically-predicted damage of 3-, 5-, and 7-ply CLT panels each subjected to 200g of C4 contact charges are discussed herein and presented in Fig. 5. For the 3-ply specimen, the numerically-predicted damage matches reasonably well with the experimental observations, whereby the predicted breach dimension of approximately 17 cm by 15 cm coincides closely with the observed breach dimensions in the testing of 15 cm by 15 cm, as shown in Fig. 5b. For the 5-ply and 7-ply CLT panels under contact charge detonations, consistent failure modes (i.e., spalling and breaching) were observed in the numerical results when compared to the overall failure geometry and mechanisms. However, the model underpredicted the extent of damage through the 5-ply and 7-ply panel depths, with the former being significantly underpredicted. Whereas full breach was observed during testing for the 5-ply specimen (Fig. 5c), the numerical model predicted limited failure, with the topmost two laminates failing. This may have been caused by the fact that severe delamination and finger joint failures were apparent in the 5-ply specimen during testing, leading to an early breach in the specimen. As the model currently treat the wood laminates as homogenous plates, it cannot yet capture such intricacies and future development of the model is required. The 7-ply specimen (Fig. 5d) was also underpredicted in terms of damage, however, in this case the representative damage was closely aligned between the experimental results and the numerical predictions.

These modelling results of CLT specimens under contact charge detonations points to the fact that the LBE method may not be appropriate for modelling contact charge detonations.





(b) 3-ply surface breach: Experimental on Left (15cm \* 15cm), FEM on Right (17cm \* 15cm)



(c) 5-ply surface breach: experimental on left (12cm \* 12cm), FEM on right (10cm \* 7cm)



(d) 7-ply surface damage: experimental on left (13cm \* 11cm), FEM on right (17cm \* 7cm)

Figure 5. Experimental and numerically-predicted damage under 200g contact charges of C4

While this modelling methodology may provide reasonable and relatively timely estimations of breach extent and damage, useful in obtaining preliminary risk and damage assessments against contact charge detonations, the ALE method is expected to provide more accurate representation of material failure and energy transfers. Work is ongoing on extending the material model and numerical model into the ALE approach, whereby the air domain, explosive charge, and specimen are explicitly modeled to accurately capture the interaction between the blast wave and the target structure.

# **5 – CONCLUSIONS**

Preliminary findings from a numerical study investigating the behaviour of CLT panels subjected to contact charge detonations and near-field blast loads were presented and discussed. An FE model developed within the LS-DYNA environment was proposed and the results were compared using full-scale experimental test results. The Load Blast Enhanced (LBE) method in LS-DYNA was used to simulate the blast loading for both loading cases, as it is computationally more efficient than other approaches, such as the Arbitrary Lagrangian-Eulerian (ALE) method. The FE model was found to predict the behaviour of CLT panels reasonably well when compared to experimental results in terms of overall failure mode, failure initiation and progression, and overall panel deformation as a function of time when subjected to near-field blast loads Preliminary modelling results have shown that such a modelling approach can be used to predict how mass-timber panels behave when subjected to contact and near-field blast loads, however, further refinements in terms of modelling methodologies to accurately capture failure modes and crack propagation in CLT structural elements, which are prone to delamination, finger joint failure, and rolling shear in the transverse laminates. Results of CLT panel specimens under the effects of contact charge detonations point to the fact that the LBE modelling methodology may not be appropriate based on the results. Future work will investigate extending and refining the model, including the application of the ALE method for such loading scenarios.

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